A New Scenario on X-ray Shallow Decay of Gamma-ray Bursts

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ABSTRACT

In this Letter, we propose that a microphysical process takes a vital role in the shocked region in which the prompt emission of GRBs is emitted. The turbulent energy is included in the internal energy transferred by the kinetic energy of the shock. It dissipates through stochastic acceleration for the electrons to supply the early X-ray emission in the phase of shallow decay. We put the constraints on the time evolution of microphysical parameters. The early X-ray fluxes can be obtained by this scenario and these results are consistent with the Swift observation.

Subject headings: gamma rays: bursts — radiation mechanisms: general — X-rays: general — turbulence — stochastic acceleration

1. Introduction

In the Swift era (Gehrels et al. 2004), the X-ray telescope (XRT) observation (Burrows et al. 2005) provides the complete light curves of gamma-ray bursts (GRBs) in the 0.2-10 keV band. One of the most interesting discoveries is the so-called shallow decay segment: the flux plateau of $F \propto t^{-0.5}$ within $10^3 - 10^4$ second after the trigger (Campana et al. 2005; De Pasquale et al. 2006). Recent statistic analyses (Nousek et al. 2006; O'Brien 2006; Liang, Zhang & Zhang 2007) have revealed that the phase of shallow decay in the X-ray afterglow might be a common feature of the long GRBs. The shallow decay in the early X-ray light curve is still a mystery, although theoretical explanations have been put forward from several aspects (see Zhang 2007 for a comprehensive review). Most of the models are: hydrodynamics of the shock by energy injection (e.g., Granot & Kumar 2006; Zhang et al. 2006), geometry of the jet (e.g., Eichler & Granot 2006; Toma et al. 2006), varying microphysical parameters (Fan & Piran 2006; Granot, Königl & Piran 2006; Panaitescu 2006; Ioka et al.

2006), late prompt emission (Ghisellini et al. 2007) or up-scattered forward-shock emission (Panaitescu 2007).

From the point of microphysics in the hydrodynamic evolution, the nature of coupling between the electrons, protons and magnetic field is complex (Chiang & Dermer 1999). Usually the simple way is to assume the equipartition between electrons, protons and magnetic field (Panaitescu & Mészáros 2006). However, in this Letter, we propose that the kinetic energy of the relativistic shocks in the plasma has been converted to the internal energy as three parts: (1) ε_B, which is the energy of magnetic field; (2) ε_e and ε_p, it means that the electrons and protons/positrons are accelerated by the shocks, normally, this is the process of first-order Fermi acceleration; (3) ε_t, which presents the turbulent energy, and this energy would sustain a relatively long time (see Section 2). The last part has not been taken into account by the former research. In our novel scenario, the relativistic electrons accelerated by the first-order Fermi acceleration emit the gamma-ray by synchrotron radiation, after the decrease of the prompt emission tail which is shown as the deep decay in the early X-ray light curve, indicating that the internal shocks are abated, the follow-up turbulence and its effects might be dominated. The turbulence could transfer its energy to the electrons via second-order Fermi acceleration, which is also called as the stochastic acceleration. Therefore, in this turbulent region, due to the resonant interaction between electrons and plasma waves, the electrons buried in the magnetic field are re-accelerated by the stochastic acceleration. The emission of these electrons dominates the shallow decay phase, until the turbulent energy dissipates and the external shock sweeps the surround medium thus the deep decay appears again.

In Section 2, we review the Fokker-Planck equation and list the coefficients associated with the turbulent term. In Section 3, the turbulent parameter ε_t, as same as ε_e and ε_B, is introduced. Due to the turbulence, these microphysical parameters evolved with time are constrained by the process of stochastic acceleration. Finally, we select these relations to reproduce the feature of shallow decay. The discussions are given in Section 4.

2. Stochastic Acceleration

The stochastic acceleration was suggested as an non-neglected mechanism to produce the high energy particles in GRBs (Waxman 1995; Dermer & Humi 2001). The numerical simulation has confirmed that the stochastic acceleration in the relativistic shocks plays an important role on the particle energy distribution and evolution (Virtanen & Vainio 2005).

In general, the charge particles are expected to be accelerated through resonant interac-

tions with the magnetized plasma waves. For this stochastic acceleration, particle distribution function $f(\gamma,t) = dN(\gamma,t)/d\gamma$ satisfies the Fokker-Planck equation, which is the kinetic equation of single electron in the energy space:

$$\frac{\partial f(\gamma,t)}{\partial t} = \frac{\partial^2}{\partial\gamma^2}[D(\gamma)f(\gamma,t)] - \frac{\partial}{\partial\gamma}[A(\gamma) + \dot{E}_L f(\gamma,t)] - \frac{f(\gamma,t)}{T(\gamma)} + Q(\gamma,t) \tag{1}$$

where $A(\gamma)$ is the acceleration rate, $D(\gamma)$ the diffusion rate, $\dot{E}_L$ energy loss rate, $T(\gamma)$ the mean escape time of electrons and $Q(\gamma,t)$ the source term. The turbulent spectrum is usually employed by the form of Kolmogorov or Kraichnan as $W(k) \propto k^{-q}$ (e.g., Zhou & Matthaeus 1990).

Park and Peterosian (1995) already explored the various analytic solutions and they illustrated that the coefficients of the equation are related to the microphysics of turbulent plasma. In that paper, they offered one special example, the so-called hard-sphere approximation, where the index of turbulent spectrum $q = 2$. This detailed work has been complemented by Becker, Le & Dermer (2006), in which the time-dependent Green's function was reexamined and the case of $q < 2$ was considered. However, the energy loss, such as synchrotron or inverse Compton, was not included in the solution.

Wang & Mao (2001) calculated the equation which is applied in the spectral variability of blazars. Recently, Liu et al. (2006) studied the stochastic acceleration in Sagittarius A* adopting $q = 2$. Under the physical conditions of Sagittarius A*, the steady state of $f(\gamma)$ was derived (Liu, Melia & Petrosian 2006). Manolakou, Horns & Kirk (2007) have obtained the time dependent solution of $f(\gamma)$ taking into account the cooling via synchrotron and inverse Compton radiation. In this Letter, the calculation is simply on the coefficients and we avoid to give any details about $f(\gamma)$.

In order to explain the shallow decay phase of GRB X-ray afterglow, assuming (i) the scatter path is much less then the length of the turbulent region, (ii) there is no continual injection and the accelerated electrons have the synchrotron cooling thus the steady state exists, we have the simplified Fokker-Planck equation of $\partial f/\partial t = 0$ and all the coefficients are time-independent. Here, we repeat the formulae produced by Dermer, Miller & Li (1996) and Wang (2002):

$$\dot{E}_L = \frac{4\sigma_T}{3m_e c}(U_B + U_{ph})(\gamma\beta)^2, \tag{2}$$

$$A(\gamma) = \frac{\pi}{2}\frac{q-1}{q}\frac{U_t}{U_B}\beta_g^2 ck(r_L k)^{q-2}p^{q-1}, \tag{3}$$

$$D(\gamma) = \frac{\pi}{2}\frac{q-1}{q(q+2)}\frac{U_t}{U_B}\beta_g^2 ck(r_L k)^{q-2}p^q\beta^{-1}, \tag{4}$$

$$T(\gamma) = \frac{\pi}{2}\frac{q-1}{q}\frac{U_t}{U_B}ck(r_L k)^{q-2}p^{q-2}(\Delta t)^2\beta^{-1}, \tag{5}$$

where $\beta = v/c$, γ is the Lorentz factor of electron, $k = (ct)^{-1}$ the wavenumber, $r_L = m_e c^2/eB$ the nonrelativistic Larmor radius of the electron, σ_T the Thomson cross section, $\mathbf{p}$ dimensionless momentum. U_B, U_t and U_{ph} are the magnetic energy density, turbulent energy density, and photon field energy density respectively. Suppose the the particles are accelerated by Alfvén turbulence, the group speed β_g is equal to Alfvén speed.

In the traditional models, two microphysical parameters, the ratio of magnetic field energy to the total internal energy $\varepsilon_B = U_B/U$ and the fraction of the total internal energy that goes into the random motions of electrons $\varepsilon_e = U_e/U$, are drawn into the study of GRBs (e.g., Sari, Narayan & Piran 1996). In our scenario, the turbulent energy is included in the total internal energy. Similar to the ε_e and ε_B, we define the dimensionless parameter ε_t to present the turbulent property as:

$$\varepsilon_t = \frac{U_t}{U}. \tag{6}$$

Since the dominant emission is synchrotron radiation during the shallow decay phase, the term of photon field U_{ph} which is associated with the inverse Compton process can be ignored. Of the single electron, the stochastic acceleration rate is balanced to the energy loss rate through synchrotron radiation:

$$A(\gamma) = \dot{E}_L. \tag{7}$$

The energy ratio of accelerated electrons in the turbulent region is equal to the total stochastic acceleration rate:

$$\frac{d\varepsilon_e}{dt} = \frac{\int A(\gamma)f(\gamma)d\gamma}{\int f(\gamma)d\gamma}. \tag{8}$$

The dissipation timescale of turbulent energy can be estimated by:

$$T_d = \frac{\varepsilon_t U}{< \dot{E}_L >} = \frac{\alpha U_B}{d\varepsilon_e/dt}, \tag{9}$$

where $\alpha = \varepsilon_t/\varepsilon_B$. The relativistic electrons re-accelerated by stochastic acceleration are assumed to have energy distribution $f(\gamma) \propto \gamma^{-p}$ with the limits of $[\gamma_{min}, \gamma_{max}]$ and produce X-ray emission. For $p = 2.2$, the timescale T_d is given by:

$$T_d = 8.6 \times 10^3 \times \alpha \times (\frac{\Gamma}{100})^{-1.6}(\frac{\varepsilon_B}{0.001})^{0.2}(\frac{n}{10^2})^{0.2}(\frac{\gamma_{min}}{10.0})^{-1.2}\ s, \tag{10}$$

where Γ is the bulk lorentz factor, γ_{min} is the minimum lorentz factor of the accelerated electron by turbulence and n is the number density of shocked medium. The dissipation

timescale of the turbulent energy is coincident with the observational timescale of shallow decay phase.

Therefore, in the shocked region with turbulence, the evolution of microphysical parameters ε_e, ε_B and ε_t can be derived from the coefficients of Fokker-Planck equation. From equation (7) and (8), we obtain:

$$\varepsilon_B \propto \varepsilon_t^{2/q} t^{2(1-q)/q} \tag{11}$$

and

$$\frac{d\varepsilon_e}{dt} \propto \varepsilon_t \varepsilon_B^{(2-q)/2} t^{1-q}. \tag{12}$$

Furthermore, in this turbulent region, we assume that these microphysical parameters have the forms of $\varepsilon_e \propto t^a$, $\varepsilon_B \propto t^b$ and $\varepsilon_t \propto t^d$. We insert them into equation (11) and (12) and put the constraints on a, b and d by two algebra equations:

$$b = 2d/q + 2(1-q)/q \tag{13}$$

and

$$a - 1 = b(2-q)/2 + (1-q) + d. \tag{14}$$

We choose the turbulent spectrum of Kraichnan with the index $q = 4/3$. All of the possible values of a, b and d are shown in Figure 1, 2 and 3.

From the standard afterglow model, the fluxes in the early X-ray band were written by Sari, Piran & Narayan (1998). There are two different limits: adiabatic and radiative case. For explanation of the emission in shallow decay phase, we obtain the early X-ray light curve under the adiabatic case as:

$$F \propto \varepsilon_e^{p-1} \varepsilon_B^{(p-2)/4} t^{(2-3p)/4} \propto t^{(bp-2b-3p+2)/4+a(p-1)}. \tag{15}$$

As an example, we adopt the index $q = 4/3$ and $p = 2.2$. Four evolutionary fluxes are achieved in the table 1, they are corresponding to the minimum and maximum values of a and b. While for the radiative case, the X-ray flux is:

$$F \propto \varepsilon_e^{p-1} \varepsilon_B^{(p-2)/4} t^{(2-6p)/7} \propto t^{b(p-2)/4+(2-6p)/7+a(p-1)}. \tag{16}$$

Table 2 lists the possible fluxes evolved with the time.

3. Discussions

Due to the turbulent energy and its dissipation in the shocked region, after the gamma-ray radiation, the electrons are re-accelerated by the stochastic acceleration and emit the

early X-ray fluxes. Therefore, the energy injection in the central engine is not required to reproduce the emission in the shallow decay phase. Our results manifest that the temporal feature in the shallow decay phase represents the process of turbulent dissipation. The microphysical parameters, ε_e, ε_B and ε_t, are varied with the time in the shocked region. Given the special values of $p = 2.0$ and $a = 0.5$ in the adiabatic case, our calculation can represent the typical observational flux as $F \propto t^{-0.5}$. Moreover, it is noted that the same shallow decay phase is also detected in the optical band as well (e.g., Mason et al. 2006), our simple interpretation is that the synchrotron emission of X-ray band and optical band may be original from the same shocked region with turbulent energy. Another advantage of our model is that the crisis of radiative efficiency (Lloyd-Ronning & Zhang 2004; Ioka et al. 2006; Fan & Piran 2006; Zhang et al. 2007) is therefore dispelled without any additional assumption of ejection/ejecta from the central engine. From this point of view, we support the internal shock pattern of standard fireball model.

In this work, we assume $f(\gamma) \propto \gamma^{-p}$ where $p = 2.2$ as the typical value. The detailed calculation of the energy distribution $f(\gamma)$ is not needed, because in our scenario the timescale of acceleration is much smaller than that of turbulent energy dissipation. Since the timescale of acceleration is also smaller than that of shock hydrodynamics, therefore, during the phase of shallow decay, the index of spectrum does not change (Liang, Zhang & Zhang 2007).

Generally, the varied values of ε_e and ε_B lead to the different hydrodynamic evolution and emissions in the entire afterglow (Mao & Wang 2001a,b). In this Letter, the early X-ray fluxes in the shallow decay phase are estimated either in the adiabatic or radiative case through the turbulent process. The average slope of radiative case is deeper than that of adiabatic case. Compared with the XRT observation, the hydrodynamic evolution of adiabatic case could be the realized regime during the shallow decay phase. Although it is hard to obtain the values of ε_e and ε_B in our scenario, we put the constraints of $\varepsilon_e \ll 1$ and $\varepsilon_B \ll 1$. More observational samples are particularly requested for the further investigations.

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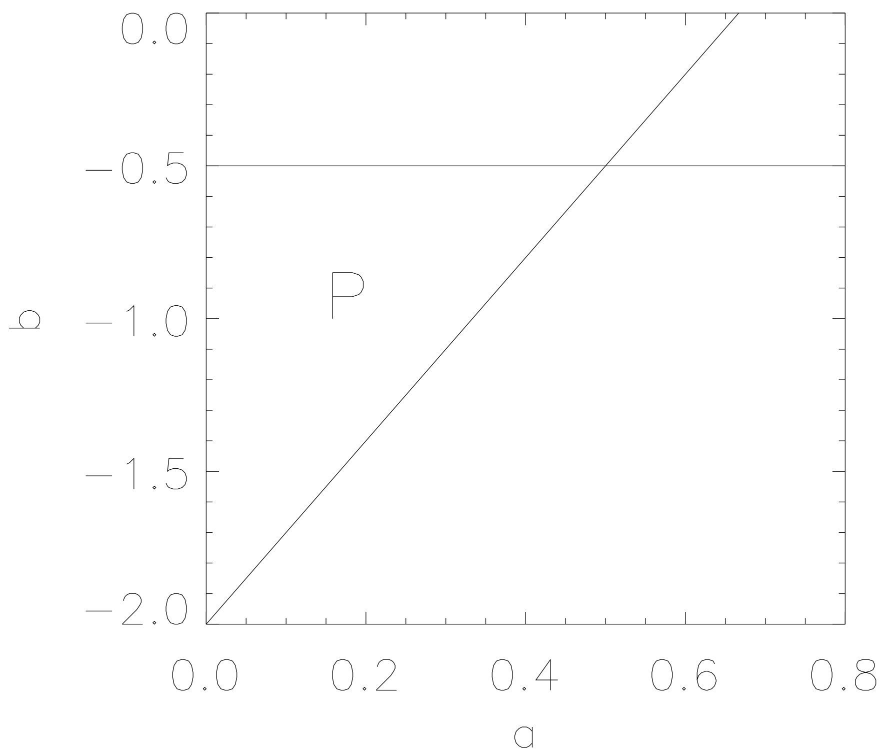

Fig. 1.— The a-b diagram. The related values of a and b are shown in the region noted by the capital P.

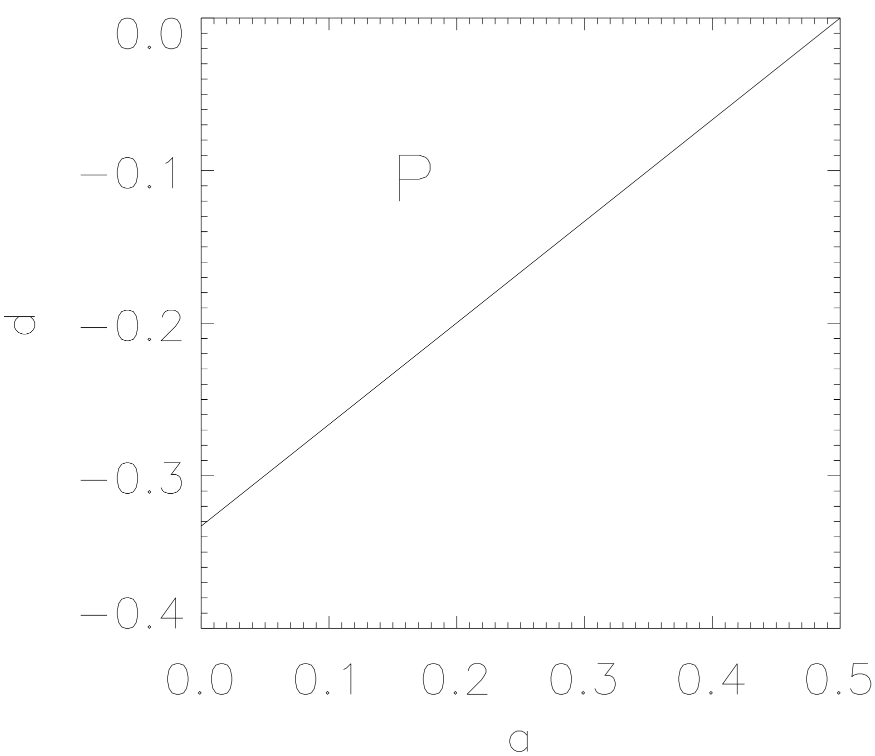

Fig. 2.— The a-d diagram. The related values of a and d are shown in the region noted by the capital P.

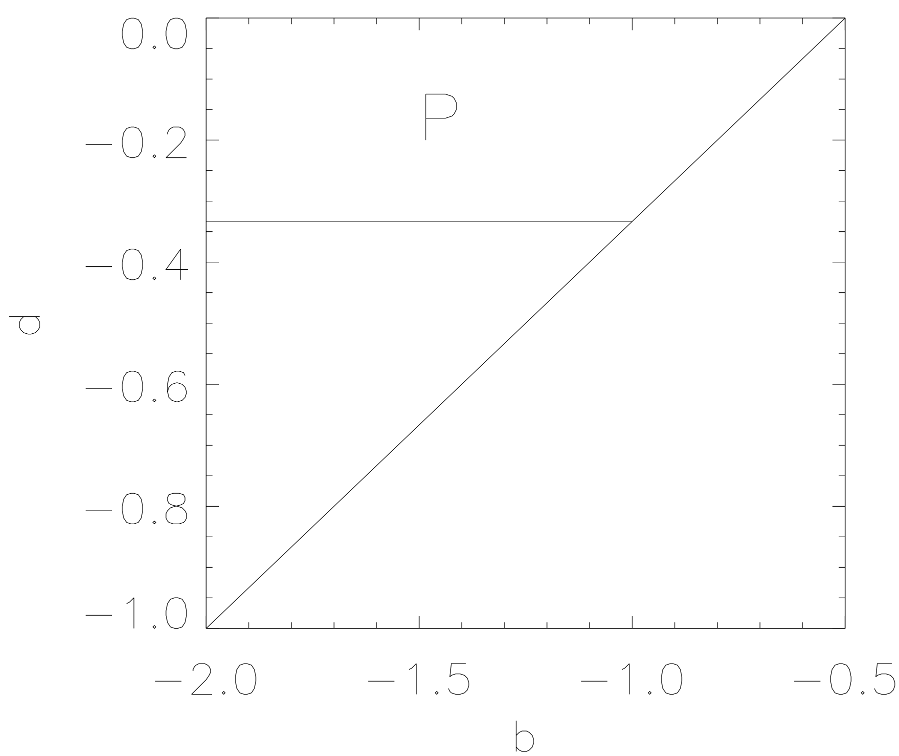

Fig. 3.— The b-d diagram. The related values of b and d are shown in the region noted by the capital P.

Table 1: The limit fluxes of shallow decay for the adiabatic case

adiabatic case	$a_{min} = 0$	$a_{max} = 0.5$
$b_{min} = -2$	$F \propto t^{-1.25}$	$F \propto t^{-0.65}$
$b_{max} = -0.5$	$F \propto t^{-1.175}$	$F \propto t^{-0.575}$

Table 2: The limit fluxes of shallow decay for the radiative case

radiative case	$a_{min} = 0$	$a_{max} = 0.5$
$b_{min} = -2$	$F \propto t^{-1.5}$	$F \propto t^{-0.9}$
$b_{max} = -0.5$	$F \propto t^{-1.575}$	$F \propto t^{-0.975}$